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Mars Surface Mobility
Comparison of Past, Present and Future Rover Systems

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Introduction: The future robotic and human exploration of Mars will rely heavily on mobile systems to meet exploration objectives. In particular, the next decade of exploration (2009-2020) will utilize rovers and other mobile surface platforms to conduct a wide variety of tasks, including the search for water and life, characterization of terrain and its geology, and making precursor measurements to prepare for future human exploration.

Objective: The objective of this study was to explore past, present, and future Mars rover concepts and compare their cost, size, and performance metrics in the context of the goals and objectives of the Mars Exploration Program. Numerous rover designs and concepts have been developed at the Jet Propulsion Laboratory, including the successful Mars Pathfinder Sojourner rover, the Mars Explorations Rovers Spirit and Opportunity, and the next generation Mars rover MSL. In addition to these rovers, numerous concept studies have also been conducted and are included for comparison purposes. The goal of this study was to explore the "continuum" rover designs over the widest possible range so that decision makers and mission planners can understand, to first order, cost and performance of future mobility systems.

Analysis: The design of future rover mobility systems for Mars depends on the type of terrain to be traversed and the type of payload investigations. Table 1 summaries the goals and capabilities of past, present, and future rover missions. As requirements on mobility, sample analysis, and number of instruments increase, so does the size of the rover. The exact dimensions and mass of the rover depend on the type power source and mobility requirements. Note that MER-C and MSL rover objectives are identical and that differences in mass are functions of mission performance, particularly the number of samples that can be analyzed.

The mobility requirement and rover wheel diameter are primary factors that determine the size and cost of mobility systems. The wheel diameter to be chosen must be large enough to avoid typical Martian hazards (i.e. surface rocks) so that linear odometer distance can be maximized while being small enough to minimize mass and power (which are related to wheel size). Rock distribution models based on Viking, Pathfinder, and terrestrial analog sites have been produced for estimating rock aerial density vs. rock size as a function of rock abundance (RA). Based on these models, Figures 1 illustrates a uniform (idealized) rock distribution for a RA = 15% and the resultant hazard density maps for different rover rock height tolerances (25, 35, 75cm). Note rock height tolerance for most rovers is nearly identical to the wheel diameter. For comparison purposes, MER wheel diameter is 25 cm, while MSL preliminary designs have been base lining 75 cm wheel diameters. We preformed an analysis on the mean free path fordifferent wheel diameters to determine optimum wheel diameter. As shown in Figure 1-2B and Figure 1-2C, the hazard density at 35 cm was significantly lower then that at 25 cm. Furthermore, the 35-cm wheel footprint was able to support the assumed weight of the rover (with instruments).

Table 1: Rover Mission Summaries

	Sojourner	MER	MER-C	MSL	AFL
Mass of Rover (kg.)	10.6	183.5	226.6	396.5	548 kg
Mass of Instruments (kg.)	~1 kg	5.5	23.6	49	114
Number of Instruments	1	6	9	11	10
Number of Samples	0	0	8	25 - 75	100
Mission Goal	Demonstrate technology, and determine the elemental abundances of surface rock.	Determine the history of climate and water at a site on Mars where conditions may once have been favorable to life.	Explore and quantitatively assess Mars as a potential habitat for life, past or present.	Explore and quantitatively assess Mars as a potential habitat for life, past or present.	Quantitatively investigate the geological and geochemical context, presence of chemical precursors of life, and preserve possible biosignatures, and begin the process of life detection.

Fig. 1-1: Viking Lander Site 1, Viking Lander Site 2; and Pathfinder Site.

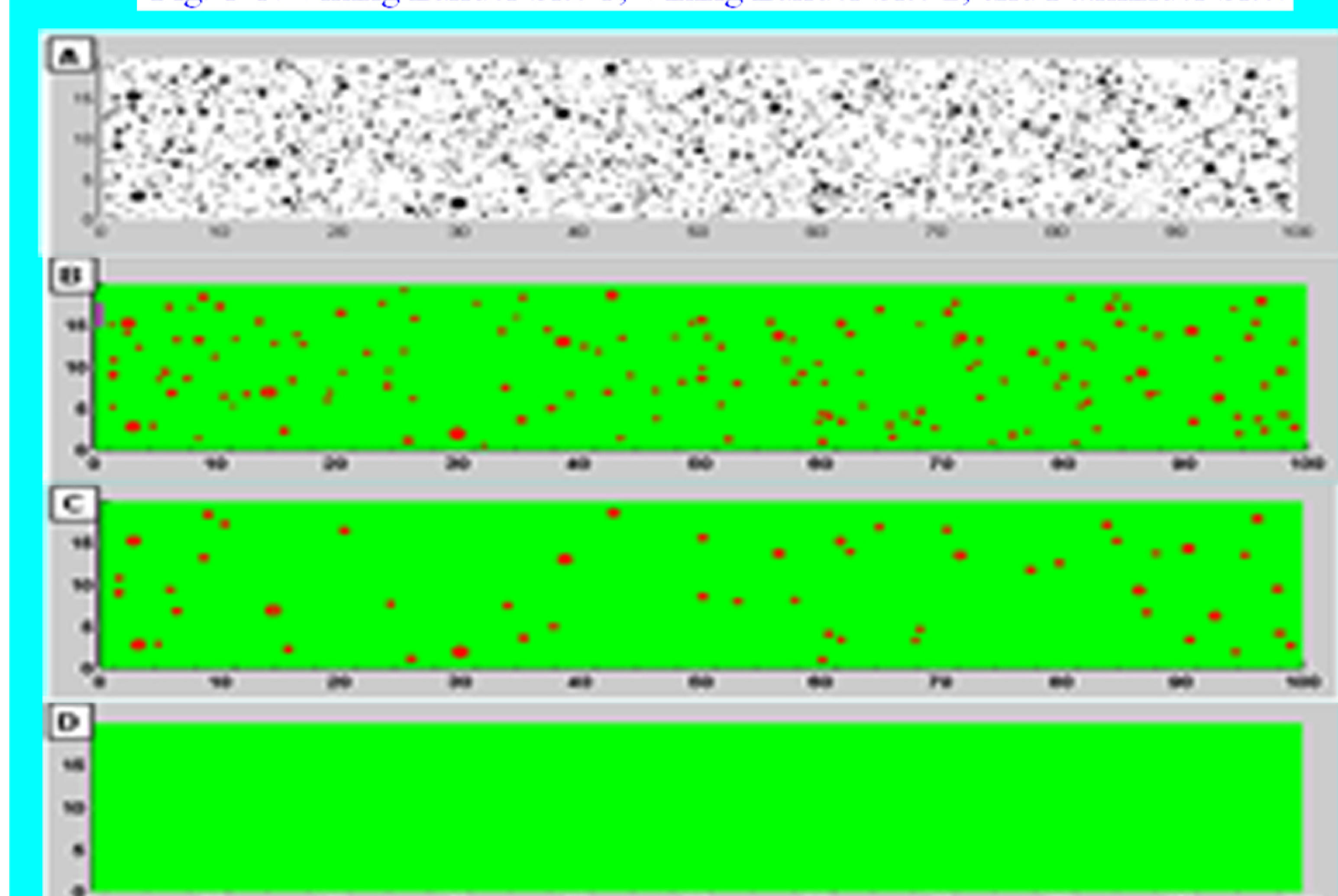
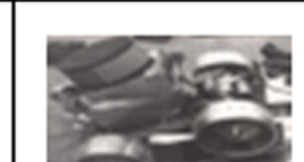
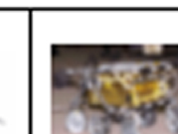
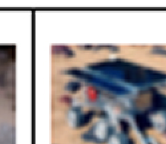
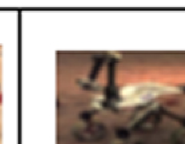
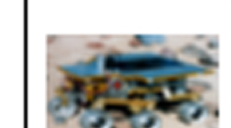
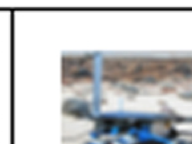
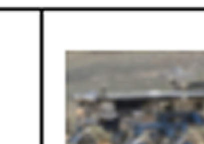
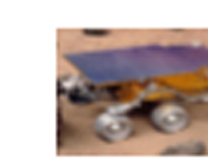
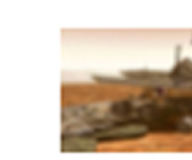


Fig. 1-2: Rock Distribution and Hazard Density for RA = 15% (Red identifies Rock Hazards with Units in Meters). A) Example Rock Distribution B) Corresponding Hazard Map for 25cm Rock Height Tolerance C) Corresponding Hazard Map for 35cm-Rock Height Tolerance D) Corresponding Hazard Map for 75cm Rock Height Tolerance.

Table 2: Planetary Rovers Compared

Rovers	Available for Flight	Testbed								Flight		Proposed Flight Rover
Type	1/5 Sojourner	1/2 Sojourner	Sojourner				1/2 Mars Exploration Rover (MER)			Sojourner	Mars Exploration Rover (MER)	Mars Science Laboratory (MSL)
	 MUSES-CN	 5-kg Rover	 Polaris	 '01 Marie-Curie	 Rocky 7	 SRR-22	 Rocky 8	 Athena	 FIDO	 Sojourner	 MER	 MSL
Mass (kg.)	1.5 – 2	5.2	9.95	10.5		10	86			10.5	168	386
Payload Capacity (kg.)	0.4	Fetch Rover	1.35			SRR-22 is a work-crew rover, i.e. no payload	33			1.35	15.5	49
Wheel Diam. (cm)	7	15.2	13			20	20			13	26	39
Power (W) (Solar unless otherwise indicated)	2.5	8	15.4			20	48			15.4	112 Max.	110 Nuclear
Sample Acquisition	None	Scoop / Rake	None		Scoop	Arm	None		Drill / Corer	None	RAT	Corer, RAT, Rock Crusher
Payload	Visible-light and infrared cameras, NIR point spectrometer, X-ray spectrometer	None	TBD			None	TBD			Alpha-proton x-ray spectrometer, 3 cameras	Pancam, Mini-TES, Mossbauer spectrometer, Alpha-proton x-ray spectrometer, Microscopic Imager	Active neutron detector, APXS, LIBS, MAHLI, MDI, MET Station, MastCam, RAD, RAT, SAM, XRD/XRF

A variety of rover systems that have been constructed are summarized in Table 2. Note that many of these rovers were never designed to fly in space, hence the size, mass, and capability are difficult to compare. However, they do serve as benchmarks for future concepts that have yet to be built.

Table 3 summarizes mass, cost, and capability, at the subsystem level, of 15 flight rover concepts studied at JPL. The cost of the rovers normalized to the payload mass and rover cost/mass relationship is highlighted in Figure 2. Not surprisingly, as the mass of a rover system increases, the cost per kilogram decreases due primarily to increases in system efficiencies. For future rover concepts, a balance must be struck between the total rover cost and system efficiencies desired. Current analyses show that rovers between 300 and 400 kg have the most overall affordability. Figure 3 highlights the cost and mass of the rover and payload.

Table 3: Proposed Mars Rovers Compared

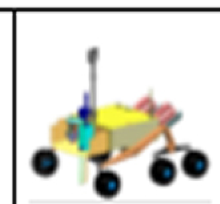
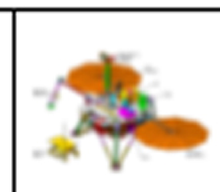
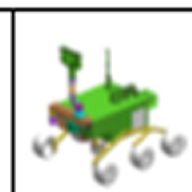
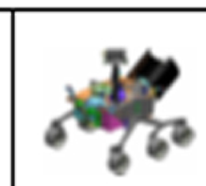
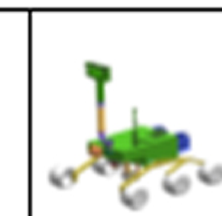
	AFL	MSL Recosting	Lunar Rover MSL	MSR Science Rover	AFL Option 2	MSL Heritage MHP Msn.	MSL Option M	MSR Fetch Rover Heritage	Lunar Rover MER	Mars Heavy Lander 2	MSL Costing	MER-C	Flight MER	MSR Fetch Pinpoint Landing	Mars Small Rover
															
Subsystem	Mass in kg / Cost in FY05$M														
ACS	11 / 22	11 / 14	17 / 19	2 / 2	9 / 25	3 / 16	3 / 20	2 / 2	8 / 18	7 / 22	4 / 26	7 / 22	11 / 1	5 / 16	5 / 12
Power	128 / 73	121 / 12	145 / 58	139 / 23	52 / 39	69 / 51	60 / 17	138 / 23	64 / 37	64 / 39	15 / 11	42 / 40	- / 0	19 / 10	25 / 27
Structures	359 / 29	356 / 36	356 / 22	175 / 30	162 / 51	174 / 38	187 / 63	132 / 29	106 / 36	120 / 38	128 / 21	114 / 39	86 / 79	52 / 35	48 / 32
Thermal	65 / 18	65 / 8	44 / 12	29 / 7	6 / 13	29 / 16	29 / 19	23 / 8	14 / 7	32 / 13	12 / 5	5 / 13	- / 4	4 / 7	14 / 9
Telecom	39 / 30	39 / 28	14 / 12	21 / 24	19 / 27	18 / 32	17 / 21	21 / 24	9 / 15	18 / 0	23 / 21	13 / 19	11 / 25	5 / 4	5 / 4
C & DH	36 / 30	30 / 23	30 / 11	30 / 18	59 / 15	16 / 7	16 / 17	30 / 18	25 / 9	15 / 0	8 / 33	23 / 10	27 / 17	9 / 7	6 / 7
Spacecraft S/W	- / 62	- / 40	- / 11	- / 27	- / 40	- / 28	- / 51	- / 13	- / 11	- / 11	- / 41	- / 15	- / 0	- / 17	- / 24
Testbeds	- / 21	- / 16	- / 14	- / 22	- / 21	- / 9	- / 23	- / 22	- / 13	- / 16	- / 33	- / 15	- / 0	- / 16	- / 10
Cabling	52 / 0	52 / 0	52 / 0	37 / 0	28 / 0	25 / 0	13 / 0	27 / 0	18 / 0	17 / 0	29 / 0	17 / 0	- / 0	12 / 0	9 / 0
Payload	159 / 231	116 / 99	86 / 85	62 / 78	88 / 156	65 / 64	72 / 90	11 / 7	61 / 50	31 / 67	57 / 137	30 / 57	15 / 23	12 / 26	4 / 16
ATLO	- / 61	- / 17	- / 16	- / 11	- / 20	- / 17	- / 18	- / 10	- / 14	- / 17	- / 36	- / 14	- / 0	- / 5	- / 15
Total	850 / 588	790 / 314	744 / 266	494 / 244	422 / 414	397 / 285	397 / 346	382 / 160	304 / 213	303 / 228	275 / 369	250 / 249	173 / 132	117 / 146	116 / 159
Wheel Diam. (m.)	0.58	0.4	0.58	-	0.25	0.4	0.4	0.2	0.25	0.2	0.4	0.25	0.25	0.2	0.2
Power	2 8-GPHS, 5080 Wh/Sol	2 8-GPHS, 5080 Wh/Sol	2 8-GPHS, 5080 Wh/Sol	2 8-GPHS, 5080 Wh/Sol	4 GPHS, 1240 Wh/Sol	8 GPHS, 2540 Wh/Sol	8 GPHS, 2540 Wh/Sol	Solar	1 8-GPHS, 2640 Wh/Sol	1 8-GPHS, 2640 Wh/Sol	2 8-GPHS, 5080 Wh/Sol	4 GPHS, 1240 Wh/Sol	Solar	Solar	Stirling 1 brick, 1152 Wh/Sol
Telecom	Relay/DTE	Relay/DTE	Relay/DTE	Relay/DTE	Relay/DTE	Relay	Relay	Relay/DTE	Relay/DTE	HDTV Relay	Relay/DTE	Relay/DTE	Relay/DTE	Relay/DTE	Relay
Landing System	Viking	Sky Crane	Sky Crane	Sky Crane	Viking	Sky Crane	Sky Crane	Viking	Viking	Viking	Sky Crane	Viking	Air bags	Viking	Viking
Lifetime	3 years	2 years	2 years	2 years	3 years	2 years	2 years	1 month	6 mon.	3 years	2 years	3 years	90 days	1 month	1 year

Fig. 2: Rover Cost / Mass

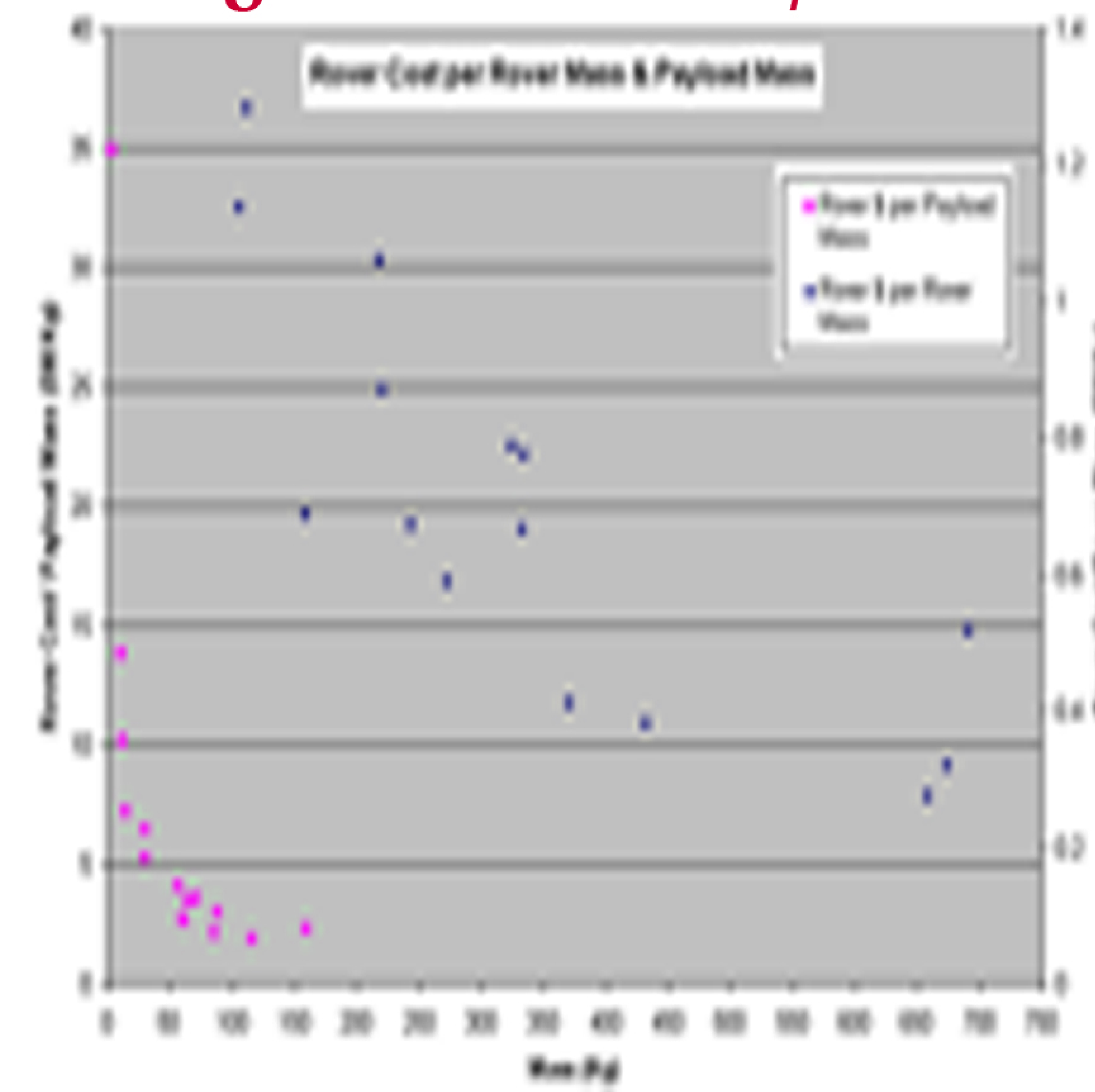
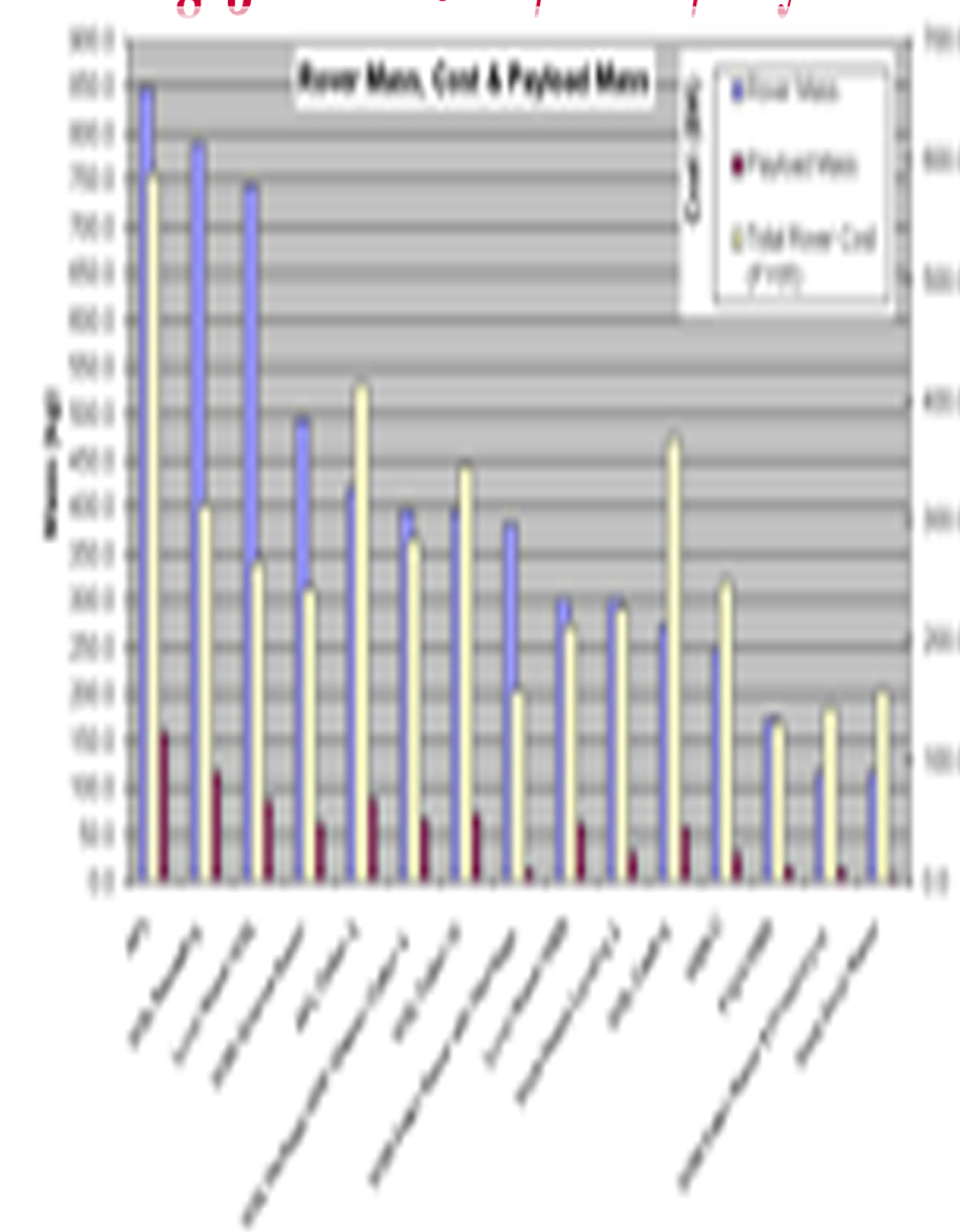


Fig. 3: Rover Cost / Mass / Payload



Conclusions: Fifteen past, present, and future rover concepts were compared. Data indicate that a "continuum" of rover cost and performance exists. As the Mars Program prepares for the next decade of exploration it is imperative that we understand the cost and performance of future mobility system.